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Policy target, feed-in tariff, and technological progress of PV in Taiwan

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ABSTRACT

It is widely recognized that solar energy, a major renewable energy source, can strengthen a country's energy security and reduce CO_2 emissions. For this reason, Taiwan aims to develop its solar power industry by promoting photovoltaic (PV) applications. To meet its PV installation targets, the government is considering adopting feed-in tariffs (FITs), offering subsidies on capital expenditures, and funding research and development. At present, there is a wide gap between the country's installed capacity and the long-term government targets. Therefore, this study constructs a PV supply curve to demonstrate the potential contribution of PV power to Taiwan's electricity requirements. Based on this curve, an assessment tool is developed to show the relationship between PV installed capacity and energy cost reductions under a FIT scheme. Using this assessment model, policymakers can simulate the adoption of PV projects at the county level and anticipate possible challenges. Furthermore, the model will also measure the level of cost reductions required for PV technology to reach specific targets under the FIT scheme.

Contents

Abbreviations: BOE, Bureau of Energy, MOEA, Taiwan, ROC; CPA, Construction and Planning Agency, Ministry of Interior, Taiwan, ROC; FIT, Feed-in tariff; MOEA, Ministry of Economic Affairs, Taiwan, ROC; PV, Photovoltaic; REDA, Renewable Energy Development Act; Taipower, Taiwan Power Company, Taiwan's state-own power enterprise; yr, year; Wp, Watt-peak; kWp, kilowatt-peak; MWp, megawatt-peak; kWh, kilowatt-hour; GWh, gigawatt-hour

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1. Introduction

The by-products from the use and generation of conventional energy contribute to greenhouse gases, climate change, and acid rain [1]. Developing renewable energy sources such as solar energy, wind power and biomass energy has become an important means of enhancing country's energy security and reducing greenhouse gas emissions [2,3]. Moreover, the recent nuclear power plant disaster in Japan has fueled doubts about the safety of nuclear power and raised questions as to whether it offers the best method of reducing greenhouse gas emissions.

Solar energy is known as an abundant, clean and renewable energy source [2,4,5]. In Taiwan, the use of grid-connected photovoltaic (PV)[1] power systems began in 2000 (see Fig. 1), relatively late compared to countries like Germany and Spain. Since Taiwan has a strong foundation in semiconductor production [6], it was not surprising when the government announced that it would prioritize the development of solar power [7], which utilizes semiconductors in its solar cells.

Economic barriers are the primary impediment to the application of PV power systems [8]. In spite of this, the modularity and easy installation of PV systems still make them a desirable option. The ideal installation size is quite broad and can range from the watt (W) to the megawatt (MW) range [9]. In addition, PV power is environment friendly, safe, and emission-free. Compared with wind turbines, PV modules are quiet, do not need high towers, produce no vibration, and do not need cooling. The PV cells also require little maintenance and are highly reliable [10,11]. The experience curve effect suggests that increasing PV deployment will reduce installation costs. Moreover, increased experience in working with this technology should provide insights into the best way to set up a grid-connected PV system. Over time, it will be possible to measure the energy conversion efficiency of PV panels. Consequently, these are the reasons the government is launching the ‘Million Solar Rooftops’ project [12].

Several mechanisms can be used to encourage the adoption of distributed solar PV systems despite the high deployment costs. Popular implementation tools include feed-in tariffs (FITs), subsidies on R&D and capital investments, and implementation of renewable portfolio standards [13]. Among these strategies, the FIT is regarded as the most effective mechanism [13–17], as demonstrated in the case of Germany [10].

The Taiwan government has shown its support for PV power development through its passage of the Renewable Energy Development Act (REDA)[2] and implementation of FIT mechanisms. With these policies in place, Taiwan's installed PV capacity has grown significantly. However, the growth rate of PV systems is still not enough to reach the target of 3100 MWp[3] by 2030. A key question is whether this is due to insufficient incentives, the sluggish deployment of PV technology, or both?

Understanding what types of areas are suitable for PV system installation is important for utility planning, accommodating grid capacity, designing financial incentives and formulating future adaptive policies. Yet, Taiwan's maximum potential installed capacity at the regional level remains controversial [18–20] because data concerning unusable areas in counties and cities are not available. Fortunately, as presented in the case studies of Hong Kong [21], Germany and Italy [22], there is a general consensus that building rooftops are feasible areas on which to install PV systems [10,13,18–20,23]. Therefore, this study estimates the available rooftops at the county level in Taiwan in order to approximate how much space can be made available for PV installation.

Past studies focused on the cost-benefit aspects of PV systems [24–26]. This method is severely limited because it does not take into account the different solar resources at the regional level, and instead uses a specific value to represent the annual generating potential of PV power for the entire country. It is important to consider what actual space is available to install PV systems to more accurately estimate capacity. Thus, the main objective of this study is to provide a clearer understanding of the potential contribution of solar PV power to Taiwan's electricity requirements, as well as the potential costs of deployment. By examining the supply curve for PV power, this paper will measure the ability of the FIT stimulus to reach the country's targeted installation capacity.

This study uses the cost of gas-fired power generation as a basis to gauge the commercial viability of PV systems because it has similar levels of CO_2 emissions. The main difference between the two energy sources is that PV power is renewable while gas is not. Due to its clean nature, gas-fired power plants are prioritized by the government and are deemed possible replacements for nuclear and coal-fired power plants. In the wake of the Fukushima nuclear plant tragedy in Japan, negotiations have started to close nuclear plants in Taiwan. This prompted the government to look to natural gas as an alternative. However, the supply of natural gas is entirely dependent on imports. Hence, the consumption of natural gas in place of coal or nuclear fuel does not improve Taiwan's energy security, whereas using PV power could promote Taiwan's energy independence.

Currently, the cost of gas-fired power generation is higher than the cost of coal and nuclear power, but gas-fired power has lower carbon emissions than coal and is much safer than nuclear power [27]. Thus, the government is planning to develop more gas-fired power systems, and Taipower (Taiwan's state-owned power enterprise) is upgrading and expanding its gas-fired power generation facilities. Statistical data from the Bureau of Energy (BOE) show that the percentage of installed capacity coming from gas-fired power generating units has been steadily increasing. By the end of 2010 (see Fig. 2), gas-fired power generation constituted 30.57% of the total power generation in Taiwan, with an installed capacity of 15,194 MW.

The rest of this paper is organized as follows: Section 2 describes the status and promotion strategies for PV power systems in Taiwan, Section 3 presents the methodology and the policy assessment tool used to analyze FITs, Section 4 details the basic assumptions underlying the analysis, Section 5 discusses the results and implications for PV power potential in Taiwan and Section 6 provides a summary and conclusions.

2. Status and promotion strategies for PV power systems in Taiwan

In 2009, the Dawning Green Energy Industry Program mapped out the blueprint for Taiwan's low carbon energy development in the future. Thus, 10% of the 500 billion NTD for the 4-year ‘Economic Revitalization Policy Project to Expand Investment in Public’ would be allocated to the development of green energy, and is projected to create a solar PV industry worth 450 billion NTD by 2015. Concurrent with expanding the scale of the industry, the government plans to expand domestic PV applications and by utilizing the experience effect between industry and the market, raise the global competitiveness of Taiwan's PV industry.

Article 6 of the ‘REDA’ set a renewable energy target of 6500–10,000 MW of domestic installed capacity, and began implementing

[1] Photovoltaic is a method of generating electricity by converting solar radiation.

[2] The Act was approved by the Legislative Yuan (Taiwan's congress) in June 2009. Its purpose is to promote renewable energy and to foster its long-term sustainability (see Article 1).

[3] MWp is Megawatt-peak. Watt-peak is a measure of the nominal power of a photovoltaic solar energy device under laboratory illumination conditions.

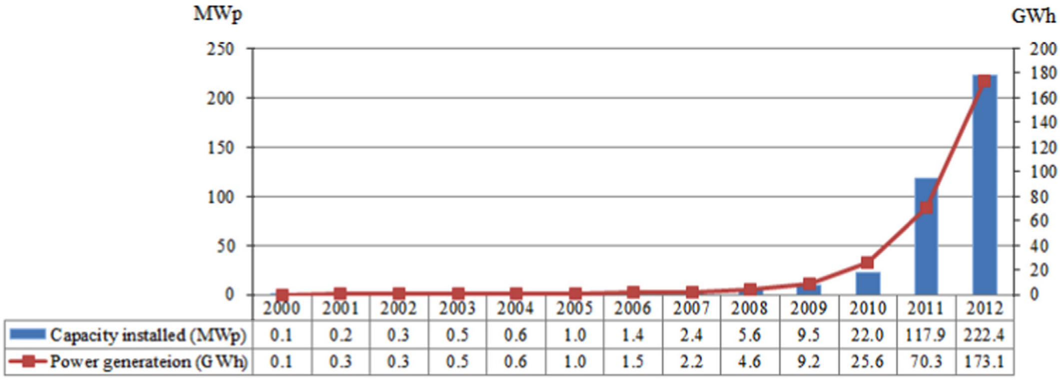

Fig. 1. Photovoltaic installed capacity and power generation.
Source: BOE [7].

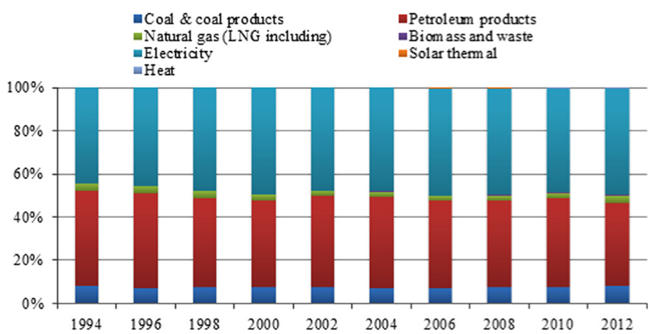

Fig. 2. Domestic energy consumption by energy form.
Source: BOE [7].

the FIT mechanism in 2009. These measures set the foundation for Taiwan's renewable energy development. The government expects to reach a PV installed capacity of 1020 MWp by 2020 and 3100 MWp by 2030 [28].

The cost of PV power generation needs to be reduced by a minimum of 26.8% to be equivalent with the social cost of gas-fired power (see Fig. 7) and make it a feasible energy option. In addition, the current installed capacity is far lower than the target, which means that success of the government policy depends critically on the effectiveness of its incentive schemes. Currently, Taiwan seeks to boost private sector investments in accordance with the relevant provisions in the 'REDA' through the use of the FIT mechanism, which is the incentive tool of choice modeled by various countries around the world [13,14].

There are two main types of FIT policies that can be applied to promote power generation from renewable energy sources. The first type is a fixed FIT, which purchases power from independent power producers using the market price plus a fixed amount over a fixed period. The second type is a premium FIT, which pays the market price plus a percentage of that amount [15]. The Taiwan government adopted the former. Previous studies concluded that the cost of PV systems is a major consideration for installers [10,29]. In order to incentivize the public to install PV systems that are more expensive than other renewable energy technologies, the FIT must be 1.5–4 times higher than for other types of renewable energy. Comparing the FIT for PV power generation in 2010 and 2011 (see Table 1), we can see that the 2011 rates dropped by 30% from 2010. This is in accordance with Article 9 of the 'REDA,' which states that the FIT should be revised to match technological improvements, change in costs, ability to achieve the target, and other factors. The government expects to maintain the financial viability of PV deployment strategies. This can be achieved by ensuring feasible costs for PV installation and allowing PV installers to have reasonable profits.

This study provides an analytical framework to explore how the FIT mechanism and technological progress can help achieve the government's PV deployment target. Energy experts have taken into account the unstable characteristics of renewable energy when setting its development targets. Lowering FIT rates would discourage PV installation among the public, which would result in unmet targets. On the other hand, higher FIT rates would lead to more PV installation, which might cause higher electricity prices because Taipower would have to purchase so much PV power. The increasing electricity prices would adversely impact public welfare [30] and affect economic development [31].

3. Methodology

3.1. Research scope

Given Taiwan's limited land area, the authors have determined that it is best to utilize building rooftops for the installation of solar PV panels. Among various possible pathways for solar PV installation, this study will explore rooftop PV systems. Taiwan has been aggressively promoting this type of installation system to avoid possible land use problems [3,12]. The rooftop PV equipment involves relatively less construction work because it only requires the installation of solar panels on the rooftops of buildings. If this project is pursued on a large scale, fewer geographical and deployment constraints can be expected.

3.2. PV power generation cost formulation

PV power generation makes use of solar energy and thus has no variable cost of fuel. The generation costs can be calculated by adding the total operational costs and the investment cost discounted based on a 20-year life cycle. This study computed the power generation costs of each PV project (with a price utility table) without considering taxes. The formula is shown below [18,32]:

$$
\begin{aligned}
&C = (FC + VC)/h,\\
&VC = FC \times M,\\
&FC = I \times CRF(r, n),\\
&CRF(r, n) = \frac{r(1+r)^n}{(1+r)^n - 1},
\end{aligned}
\tag{1}
$$

where C denotes the levelized cost of PV electricity (NTD/kWh); VC is the annual variable cost (NTD/kW per year); FC is the annual fixed cost (NTD/kWp per year); h is the annual full-load working hours (hours/year); M is the operating and maintenance expense ratio (%); I is the

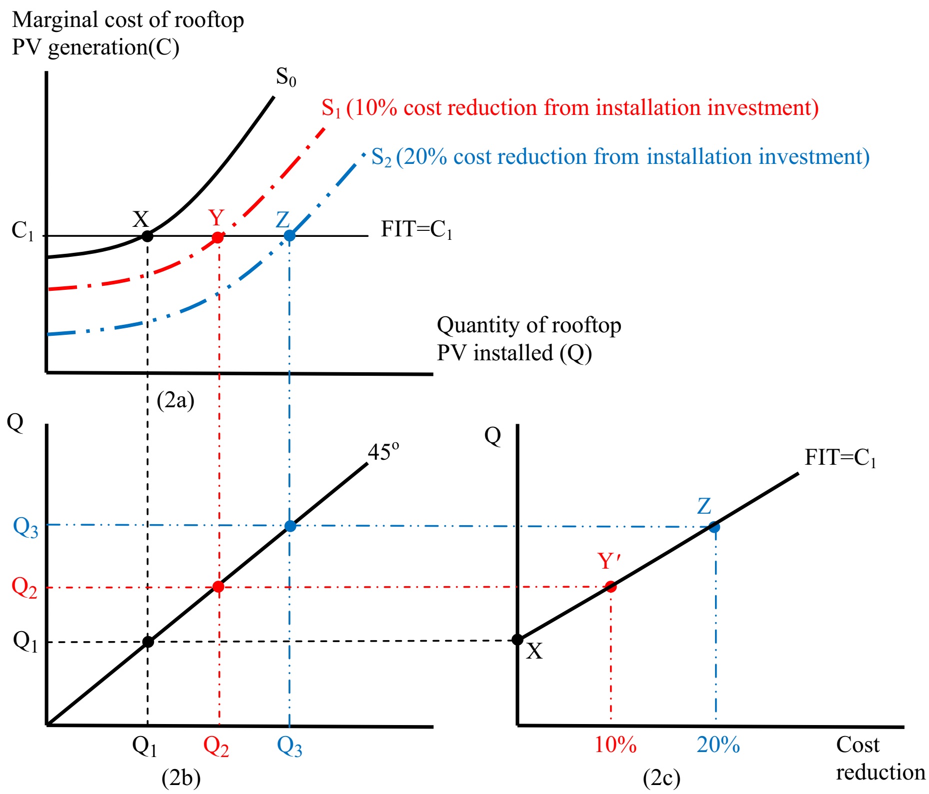

Fig. 3. Relationship between cost-reduction and government target under a specific FIT.
Cost reduction rate = (marginal cost–FIT rate)/marginal cost.

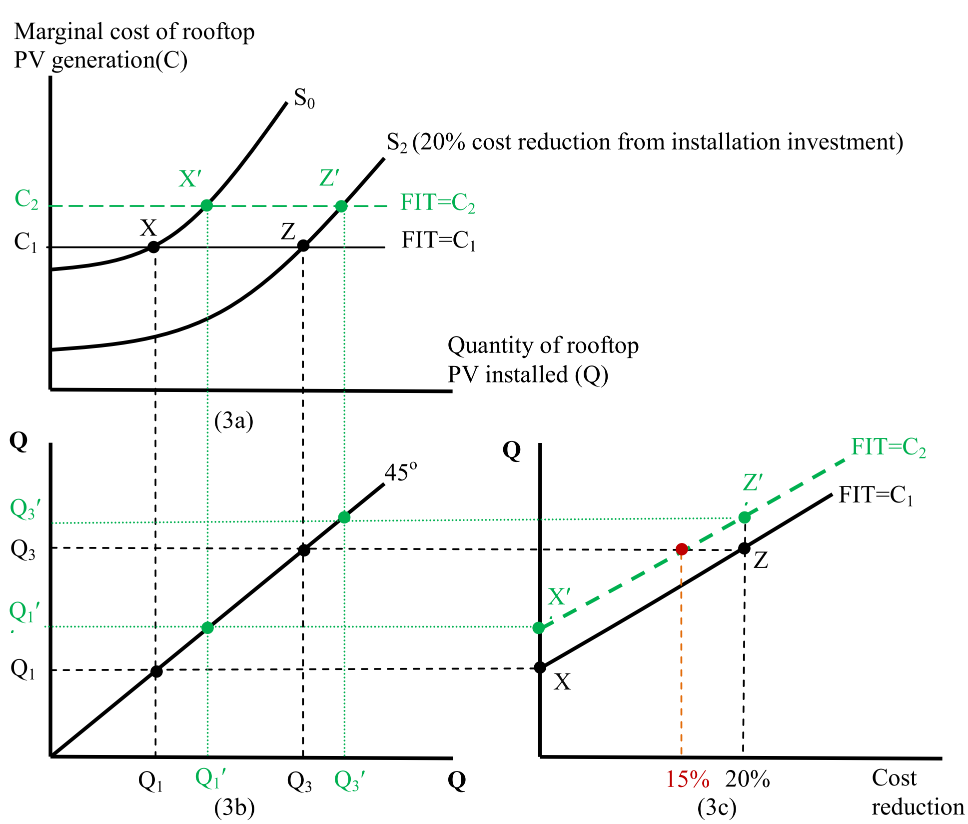

Fig. 4. Relationship between cost-reduction and government target under different FITs. See footnote in Fig. 2.

Table 1
Feed-in tariffs of PV in Taiwan.
Source: BOE [7].

Unit: NTD/kWh	Category	2010	2011	2012 first half	2012 second half	2013 first half
Rooftop	≧1– < 10k Wp	11.1883	10.3185	9.4645	9.251	8.3971
	≧10– < 100 kWp	12.9722	9.1799	8.5394	8.3259	7.5432
	≧100– < 500 kWp		8.8241	8.1836	7.9701	7.1162
	≧500 kWp	11.1190	7.9701	7.3297	7.1873	6.3334
Ground mounted	Indifference		7.3297	6.9027	6.7604	5.9776

Since 2012, the FIT rates for PV have changed twice a year as opposed to annual changes in the past.

Table 2
Ground floor areas from 2000 to 2009.
Source: CPA [34].

Ground floor areas (m^2)		Share (%)
Within urban planned district		
Residential district	23,628,051	50.93
Commercial district	3,409,104	7.35
Industrial district	11,372,060	24.51
Administration district	749,017	1.61
Education district	3,835,531	8.27
Outside urban planned district		
Residential district	3,398,324	7.33
Total	46,392,087	100

investment cost (NTD/kWp); *CRF* is the capital recovery factor; *r* is the reasonable profit rate (discount rate, %); and *n* is the life span of PV equipment measured in years.

This study uses the area available on Taiwan's building rooftops at the county level as the basis for a techno-economic analysis of crystalline wafer-based PV modules. There are two limiting constraints to the installation of rooftop PV systems. The first limiting factor is the total installed capacity available for PV equipment (see Table 2), and the second is the effective utilization rate of sunlight at the installation location (see Table 5). Using data on solar resources and the investment costs of PV deployment projects (see Table 6), the generation costs of each project are calculated as shown in Eq. (1), and serve as the basis for Taiwan's PV supply curve.

The PV supply curve attempts to estimate the relationship between the cost of a PV project and the quantity of PV installation at or below that cost. If the power generation cost of PV power can compete with that of traditional electricity sources, the quantity at or below that cost would be determined by supply. This permits a generalized treatment of deployment potential in the cost analysis, and provides a consistent accounting framework [33]. This also offers a financially conservative assessment tool to evaluate the PV deployment policy (see Section 3.3).

To determine the potential scale of PV power generating installations in Taiwan, this study uses gross ground floor areas from 2000–2009,[4] based on statistics from the Construction and Planning Agency [34], to predict the maximum rooftop surface area available. The NASA climate database, which uses the RETScreen model [35],[5] is used to measure the amount of sunlight at county level. This study does not include customs and taxes in the computation of the deployment costs of PV equipment; instead it uses the discounted life cycle costing method. Therefore, the cost of PV power generation (NTD/kWh) is mainly comprised of investment and operation costs.

[4] Ground floor areas refer to the area of a building suitable for construction.

[5] RETScreen is an excel-based clean energy project analysis software tool to model any clean energy project. It is designed for use by decision makers to conduct various analyses pertaining to energy, cost, emissions, the market, sensitivity and risk. However, this study uses the embodied NASA climate database to estimate the solar PV resources of various counties/cities in Taiwan.

3.3. A policy assessment tool based on the PV supply curve

The PV supply curve shows a gradual increase in solar PV quantity with cost. In order to meet the PV installation targets, we can assume that the government would utilize areas with high levels of sunlight first, and then would continue with installations in areas with less sunlight. This means that production costs would start out low and then would gradually increase as the output level per installed PV panel decreases due to decreasing amounts of available sunlight. The steep increase in the supply curve as the quantity of installed PV increases can be explained by the accelerating rate of sunlight reduction as solar PVs are installed in areas with progressively reduced amounts of sunlight. This is the main limitation of this research, and it also represents one of the major challenges to Taiwan's rooftop PV installation project.

The supply curve in Section 5.2 shows the high cost of PV power, the reasons for which can be explored by examining the primary considerations in commercializing PV systems. To do so, this study compares the financial and social costs of gas-fired power and PV power generation, including discount rates, technological improvements and external costs.

Fig. 3 shows that the required cost reductions to meet the government target are determined by the FIT and the quantity of PV installations. As mentioned in Section 3.2, the production costs of PV power are determined based on the capital investment, operating and maintenance costs, PV module life span, reasonable profit rate, and annual full-load working hours. This paper demonstrates the FIT rates and cost reductions required to achieve the government target, ceteris paribus.

Point X along the supply curve in graph (3a) shows that FIT$=C_1$, which also equals Q_1 in graph (3b) and graph (3c). Currently, installations are only feasible at the level represented by Q_1. Graph (3c) shows that a 20% cost reduction in PV panel installations is required in order to move to Q_3, which would meet the PV installation target under the FIT.

Fig. 4 illustrates what needs to be achieved to close the gap between the current level of production and the adjusted government target. This target was adjusted to accommodate the experience curve and improvements in conversion efficiency. In this section, three graphs labeled graph (4a), graph (4b) and graph (4c), serve as a basis for policy assessment. Graph (4a) shows the supply curve denoted by S_0, with the quantity of installed PV panels plotted on the *X*-axis, and the cost of production plotted on the *Y*-axis. Suppose that the current FIT is at point *X* that equals C_1, this represents the reference point from which we can start moving toward the target. The FIT is expected to decrease every year because its main component, initial investment, goes down each year due to decreasing costs of solar panels, which are classified as a process improvement.

The government target is assumed to adjust periodically based on two time-related factors: technology or conversion efficiency improvements, and process improvements. The new target should have the same FIT and the same cost of production, but a different quantity of

Table 3
Potential installed capacity in counties/cities.

County/city	Ground floor areas (m^2)	Potential areas[a] (m^2)	Potential installed capacity[b] (MWp)	County/city	Ground floor areas (m^2)	Potential areas[a] (m^2)	Potential installed capacity[b] (MWp)
Taipei County	7,231,985	5,857,908	586	Taitung County	274,980	222,734	22
Yilan County	880,154	712,925	71	Hualien County	660,183	534,749	53
Taoyuan County	6,671,898	5,404,237	540	Penghu County	186,269	150,878	15
Hsinchu County	2,103,864	1,704,130	170	Keelung City	455,540	368,987	37
Miaoli County	1,109,439	898,645	90	Hsinchu City	1,178,935	954,937	95
Taichung County	2,743,588	2,222,306	222	Taichung City	2,786,881	2,257,374	226
Changhua County	1,867,612	1,512,766	151	Chiayi City	528,841	428,361	43
Nantou County	1,003,710	813,005	81	Tainan City	1,466,383	1,187,771	119
Yunlin County	1,171,825	949,178	95	Taipei City	4,682,153	3,792,544	379
Chiayi County	657,105	532,255	53	Kaohsiung City	2,546,279	2,062,486	206
Tainan County	2,440,973	1,977,188	198	Kinmen County	146,178	118,404	12
Kaohsiung County	2,160,529	1,750,029	175	Lienchiang County	12,297	9961	1
Pingtung County	1,424,485	1,153,833	115	Total	46,392,087	37,577,590	3758

[a] Potential area = ground floor area × 80% (usability rate of ground floor area).
[b] Each kWp requiring 10 m^2 of ground area.

Table 4
Parameters to calculate the capacity factor of PV power projects.

Key factor	Value	Key factor	Value
PV capacity per unit (kWp)	1	Conversion efficiency (%)[b]	10
Solar collection area (m^2)	10	Invert efficiency (%)[c]	90
Temperature coefficient (%)[a]	0.40		
Working temperature (°C)[a]	45		

[a] The setting values retrieved from the defaults of the REScreen Model [35].
[b] See Chen et al. [2].
[c] The efficiency of PV inverter is at least 90% or more.

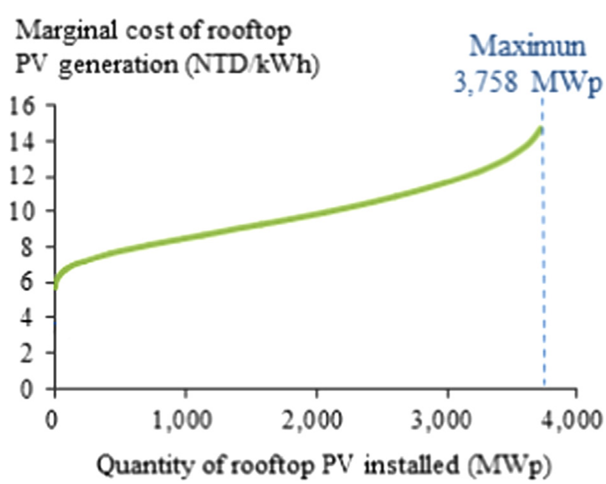

Fig. 5. Aggregate supply curve of different PV capacity classes in counties/cities.

installed PV equipment. This is demonstrated by the line connecting *X* and *Z* on graph (4a). In graph (4c), we show the relationship between the quantity of installed PVs and cost reductions.

At the current FIT = C_1, Q_1 is the quantity of PV systems installed. At some point in the future, there is a new target denoted by Q_3. Graph (4c) shows that in order to achieve this target (Q_3), we need to reduce costs by 20%. This can be achieved if the government invests more in R&D or encourages the private sector to invest more in R&D. Moreover, the government can examine if the cost reduction/PV installed quantity (choose one) denoted by Q_3 is enough to achieve the CO_2 emission target by using PV power. If Q_3 is not enough to achieve the CO_2 reduction target, then the government can raise the FIT to move from Q_3 to Q_3'. These possible solutions can be classified as conversion efficiency improvements.

To achieve the government's PV power production targets, it is important to eliminate economic barriers especially in the early stages of industry's development. A carefully planned FIT mechanism can help achieve this and would ensure sound fiscal management. Having FIT rates that are too high would put unnecessary financial burden on the government and would lead to excessive purchases of renewable power [30]. The government needs to regularly assess whether it is still purchasing renewable power at the optimal level. This can be done through continuous evaluation of the FIT rates and target PV installations.

Graph (4c) can be used as a tool for policymakers to test the feasibility of achieving the target PV installations given the market's ability to meet the demand for PV solar panels.

4. Parameters and basic assumptions

4.1. Reference costs: gas-fired power generation

Existing gas-fired power generation technology is considerably mature; therefore the prospect of lowering generation costs is extremely limited. Due to the lack of data on the costs of land, plant, equipment, and operations and maintenance (O&M), this study adopts a purchasing cost of 3.45 NTD/kWh from the private sector as the basis for estimating gas-fired power generation costs in the future [36]. The gas-fired power costs can serve as a reference cost in comparison with commercial PV power generation.

4.2. Environmental costs of gas-fired power generation

Gas-fired power plants emit air pollutants such as CO_2, SO_x, and NO_x that are damaging to the environment. A proper understanding of their impact on the environment is necessary to calculate the environmental costs of gas-fired power generation. Therefore, this study takes the Tunghsiao power plant as the standard for measuring pollutants emitted in gas-fired power generation.

The new facilities built at Taipower's Tunghsiao power plant use the integrated gasification combined-cycle project with standalone installed capacity of 720 MW, a power generation efficiency of approximately 56.7–58.4% (LHV gross, ISO condition), a heat rate of 1.665 kcal/kWh, and annual electricity usage of 5694 h (capacity factor[6] of 0.65). Pollution data show 0.41–1.43 mg/m^3 (0.14–0.5 ppm) of Sulfur and a 20 ppm concentration of NO_x from

[6] The value derived from the annual full-load working hours divided into 8760 h (365 days × 24 h). This value can account for the power generation performance of power equipment.

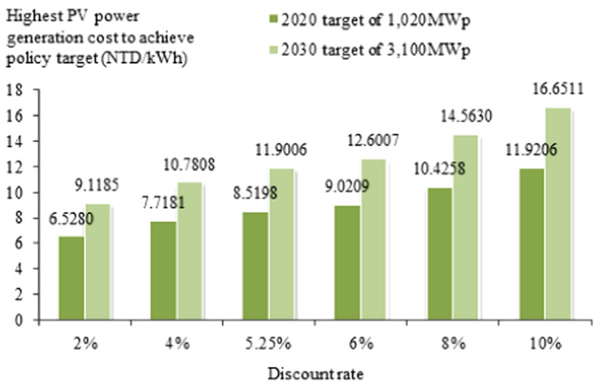

Fig. 6. Sensitivity analysis of discount rate.

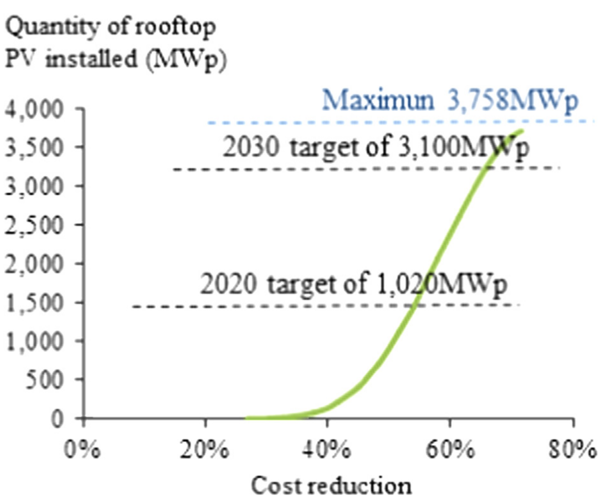

Fig. 7. Cost reduction required in PV power compared with gas-fired power. Cost reduction rate= (PV power generation cost- gas-fired power generation cost)/ PV power generation cost.

Table 5
Capacity factor[a] of PV power projects in counties/cities.

County/city	Max.	Min.	County/city	Max.	Min.
Taipei County	0.132	0.078	Taitung County	0.147	0.083
Yilan County	0.137	0.080	Hualien County	0.142	0.083
Taoyuan County	0.144	0.078	Penghu County	0.156	0.085
Hsinchu County	0.155	0.086	Keelung City	0.143	0.078
Miaoli County[b]	0.155	0.086	Hsinchu City	0.155	0.086
Taichung County	0.154	0.085	Taichung City	0.154	0.085
Changhua County	0.147	0.083	Chiayi City	0.160	0.091
Nantou County[b]	0.147	0.083	Tainan City	0.172	0.090
Yunlin County[b]	0.147	0.083	Taipei City	0.132	0.078
Chiayi County	0.160	0.091	Kaohsiung City	0.171	0.097
Tainan County	0.159	0.098	Kinmen County	0.148	0.086
Kaohsiung County	0.171	0.097	Lienchiang County	0.131	0.079
Pingtung County	0.178	0.098	Total	0.178	0.078

[a] Capacity factor = annual full-load working hours/(365 day × 24 hour).
[b] Due to lack of observation information of Miaoli County, Nantou County and Yunlin County in the NASA climate database, this study adopted Hsinchu County data as Miaoli County data, and Changhua County data as Nantou County and Yunlin County data.

Table 6
Financial parameters of PV.
Source: BOE [7].

Parameter	Value
Initial capital investment	
Category I (1–10 kWp)	118,000 NTD/kWp
Category II (10–100 kWp)	106,000 NTD/kWp
Category III (100–500 kWp)	100,000 NTD/kWp
Operation and maintenance	0.7%
Discount rate	5.25%
Economic life	20 years

gas combustion. The presence of suspended particles in the clean natural gas is minimal, and thus negligible.

The process of computing the environmental costs starts by measuring air pollutants emitted by the gas-fired power plant. Using the emissions data for the respective pollutants, the NO_x emission coefficient is computed to be 2.358×10^{-4} kg/kWh, while the SO_x emission coefficient is 5.895×10^{-6} kg/kWh. As for CO_2, this study uses Hondo's [37] life cycle CO_2 emission factor of 0.519 kg/kWh.

Next, to obtain the external costs of gas-fired power the air pollutant's emission coefficient is multiplied by the environmental costs due to air pollution. Because it is difficult to estimate the environmental costs, this study adopts Liang's [38] predicted costs of 53,790 NTD/ton for NO_x, 45,919 NTD/ton for SO_x, and 1400.7 NTD/ton for CO_2. Based on these data the external costs of each air pollutant produced by gas-fired power are: NO_x at 0.0127 NTD/kWh, SO_x at 0.0003 NTD/kWh and CO_2 at 0.727 NTD/kWh. These results show that the total external environmental cost of gas-fired power is 0.74 NTD/kWh.

4.3. Potential deployment of PV

As stated previously, the success of PV equipment installations lies in the available area on building rooftops. In order to reasonably estimate the area suitable for installing PV equipment, this paper uses the ground floor area of Taiwan buildings from 2000 to 2009 [34]. This study set the usability rate of ground floor area as 80%, with each kWp requiring 10 km^2 of ground area, to measure the future deployment potential of PV systems in Taiwan. The calculations based on these data indicate that 46,392,087 km^2 of ground area can accommodate 3758 MWp of installed capacity. Thus, by solely considering the ground floor area, it is possible to achieve Taiwan's installation targets of 1020 MWp by 2020 and 3100 MWp by 2030.

Due to a lack of detailed ground floor area statistics and capacity classes for the various counties and cities (e.g., residential/commercial/industrial), this study gathered all of the first time registered data for ground floor area of buildings between 2001 and 2009, obtaining the ground floor area of the various counties and cities as well as their respective percentages. The ground floor area percentages are multiplied by the gross ground floor area of 46,392,087 km^2 to obtain the ground floor area allocated to each county or city. These data can then be used to predict the scale of PV deployment as shown in Table 2.

The annual conference held in 2011, which decided the FIT rates for renewable energy power, mentioned that in order to avoid affecting deployment on state land, the government encouraged the installation of rooftop PV systems and classified it into four capacity classes: 1–10 kWp, 10–100 kWp, 100–500 kWp, and above 500 kWp. Different installed capacities have corresponding differences in initial installation costs. Due to ground floor area considerations, it is important to note that the smaller installation capacities are more suitable for residential areas while the bigger capacities are suitable for industrial/commercial areas. The percentage of land occupied by these different types of areas is shown in Table 3, which accounts for the whole land area of Taiwan. Actual data on individual counties and cities are currently not available. For this reason, this study is limited in that it uses the aggregate data to determine how the different capacity classes

would be distributed across Taiwan. If data on each county/city become available, then a more accurate distribution of capacity classes can be made for each county/city. The 500 kWp capacity class presents a considerable implementation challenge since it requires more than 5000 km^2 of installation area, and therefore will not be discussed here.

Table 3 shows that 58% of the gross ground floor area is comprised of residential areas, which means that there is a higher deployment potential for the 1–10 kWp capacity class. Industrial areas constitute 25% of the ground floor area, which represents the 100–500 kWp capacity class. Therefore, this study allocated 50%, 25%, and 25% to the PV capacity classes 1–10 kWp, 10–100 kWp, and 100–500 kWp, respectively. For example, the total deployment potential for Taipei County is 586 MWp (see Table 2) and belongs to the third category of capacity classes mentioned above. The first installation category (1–10 kWp) is 292 MWp in scale (50%), with both the second (10–100 kWp) and the third (100–500 kWp) categories being 146 MWp (25%) each in scale.

4.4. Capacity factors of PV power projects

This study uses the RETScreen model [35] to measure the capacity factors of various counties and cities. This process starts by obtaining the climate information for the various counties and cities in Taiwan from the NASA climate database. Next, the technical setting for the crystalline silicon PV equipment is determined from the computing parameters in Table 4 (such as solar cell efficiency, converter efficiency, and change in temperature) in order to compute the potential electricity output. As described in Section 3.2, there can be different amounts of electricity usage hours within the same county or city. In order to compute the largest and smallest capacity factor, this study set 23.5° and 90° as the PV module inclination angles in RETScreen. Since the actual amount of sunlight is unknown, this paper adopts the estimated capacity factor of 0.078–0.178 (see Table 5).

The potential capacity of every county is then divided into the different installation sizes based on their electricity usage hours. For example, in Taipei County, the largest electricity usage is 1159 h while the smallest is 687 h, so the potential capacity can be divided into 473 PV projects ($=1159-686$). The total deployment potential in Taipei County is calculated to be 58 l MWp, as shown in the previous section (see Table 2). The first category of installed capacity class (1–10 kWp) can have a deployment scale of 293 MWp; while both the second category (10–100 kWp) and the third category (100–500 kWp) can have a deployment scale of 146 MWp. These three installation scales could translate into 473 projects, which means that Taipei County can have a total of 1419 PV power generation facilities ($=3\times473$). Projects under the first capacity class can each have a 619 kWp installed size, while both the second and third classes can have a capacity of 310 kWp.

The potential installation size and capacity factor for each project are estimated using the aforementioned method. The power generation costs and volume of each project can then be calculated by determining the PV investment cost before analyzing the PV supply curve in Taiwan.

From Eq. (1), the PV power generation cost is determined using the initial installation costs and electricity usage hours. The electricity usage hours are shown in Table 5. This study used evaluated values from the BOE for the PV initial investment costs and operational costs as financial parameters [7] (see Table 6).

5. Results and discussions

This section shows a diagram of Taiwan's PV supply curve by arranging the PV projects according to power generation costs in ascending order. In Fig. 5, the Y coordinate represents the cost of PV power generation while the X coordinate represents the total scale of PV deployment. The upward tilting supply curve shows that the PV project with the lowest cost of power generation is 6.4317 NTD/kWh, while the highest cost project is 17.2263 NTD/kWh based on these results.

The supply curve shows that the potential capacity that can be used for rooftop PV deployment in the future is 3758 MWp (generating approximately 3847 GWh/yr). Not considering deployment costs, the average yearly electricity usage in Taiwan is 1024 h, which is lower than the 1250 h computed using the 2013 FIT formula [7]. This could mean that the government calculates FIT rates based on the abundance of solar energy resources in different areas.

5.1. Evaluation of PV deployment potential

Taiwan's policymakers and energy experts have yet to reach a consensus on PV installation potential. Table 7 shows the predicted installation potential according to various researchers. Among them, Chen et al. [2] estimated a PV system potential with a total area of 582.2 km^2 and an estimated power generation potential of 65 TWh per year, 15.5 and 16.9 times larger than the values estimated by this paper, respectively. However, existing standards of photoelectric conversion technology and the high deployment costs can impede Taiwan's adoption of solar resources in the near future. Chen et al. [2] might have made an estimate which is far too optimistic. National studies conducted on the potential of PV deployment have come up with similar results to this study, ranging between 2855 and 6166 MWp. In addition, Table 7 shows that although this paper estimated a higher PV deployment potential than the BOE's estimate of 2855 MWp and lower than the INER's estimate of 6166 MWp, it is nevertheless similar to the estimate made by the Bureau of Energy Commission under the Ministry of Economic Affairs at 4500 MWp in the year 2020 [20]. Likewise, it is also close to Taipower's own estimate of 4131 MW.

5.2. The primary considerations of PV technology

The high cost of PV power generation is a challenge shared by various countries around the world. Lowering the generation costs can be a direct solution to make PV power a reality in Taiwan. This section explores the different ways to achieve more cost-effective PV power compared to gas-fired power generation. This can be done by: (1) advocating for technological advancement in solar energy to reduce power generation costs to below that of gas-fired power plants, (2) calculating the environmental costs of gas-fired power generation that result from carbon dioxide and other emissions that are not present in solar energy, and (3) presenting the evidence that the government can help reduce the cost of power generation and increase PV system capacity by lowering interest rates on loans. This paper also presents a sensitivity analysis that shows how the installation of PV systems is affected by the costs of PV technology. Bloomberg's New Energy Finance estimated that the costs of PV technology would go down significantly by the year 2020.

Table 7
Comparison of Taiwan's PV potential assessments.

	Potential assessment
Energy Commission under MOEA [21]	4500 MWp
Chen et al. [2]	75,000 MWp (65 TWh/yr)
BOE [23]	2855 MWp
INER [23]	6166 MWp
TaiPower [23]	4131 MWp
This study	3758 MWp (3847 GWh/yr)

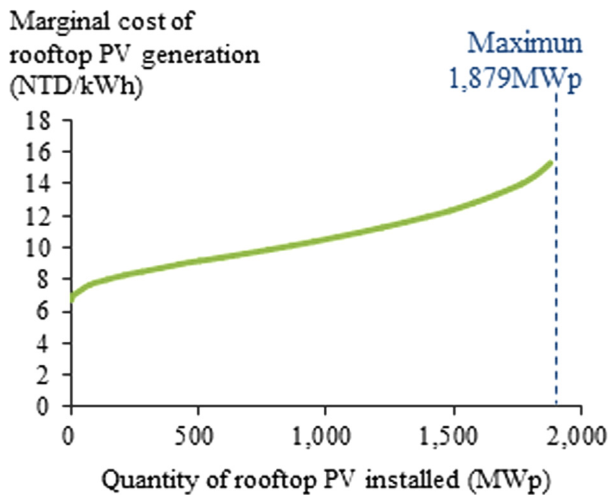

Fig. 8. Supply curve of the first PV capacity class (1–10 kWp).

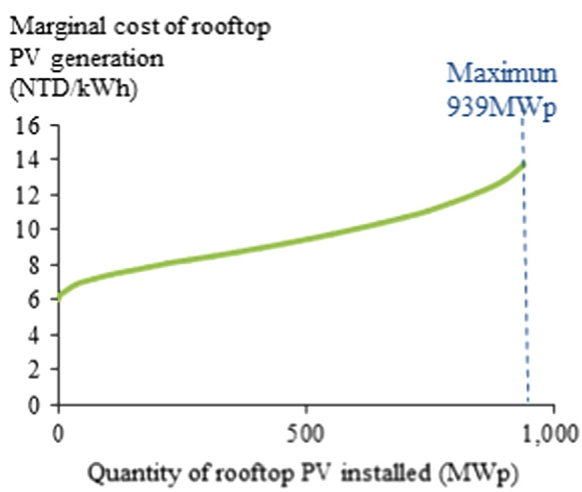

Fig. 9. Supply curve of the second PV capacity class (10–100 kWp).

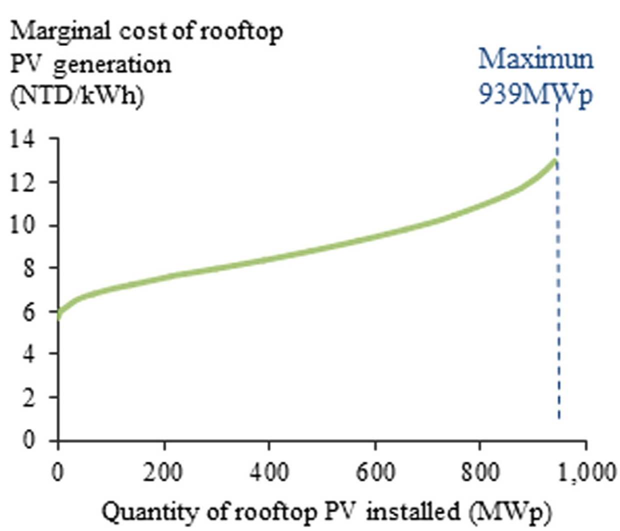

Fig. 10. Supply curve of the third PV capacity class (100–500 kWp).

This study selected gas-fired power as a reference fuel to use in determining the commercial feasibility of PV power because of its similar nature to PV power generation. In the event that PV power cannot be fully implemented for financial reasons, gas-fired power would be the next best alternative to augment power generation capabilities during peak-load hours. As per Sections 4.1 and 4.2, the social cost of gas-fired power is about 4.19 NTD/kWh, calculated as the sum of the generation cost (3.45) and external cost (0.74). As seen in the supply curve in Fig. 5, the individual costs of various PV systems are all above 4.19 NTD/kWh, showing that PV technology cannot currently compete on price and would require the government's support to promote its application.

The external cost of gas-fired power, the alternative clean energy solution, is 0.74 NTD/kWh (described in Section 4.2). The external costs specific to air pollution (including NO_x and SO_x), and CO_2 are 0.013 NTD and 0.727 NTD, respectively. The cost of CO_2 emissions constitutes as high as 17.35% of the total social costs of gas-fired power (=0.727/4.19). This alarming fact calls for urgent measures to develop cleaner energy, such as PV power. Furthermore, in the face of frequent abnormal climate phenomenon, nations around the world are putting more effort into addressing the problem of high CO_2 emissions through the development of renewable energy.

Since Taiwan does not have a carbon trading system, there is no specific standard for determining the price of carbon to date. Therefore, this study adopts the external cost of 1400.7 NTD/ton mentioned by Liang [38] as the CO_2 price. The CO_2 emission cost of gas-fired power generation is then multiplied by the gas-fired technology carbon emission coefficient of 0.519 kg/kWh [37]. Generally, when the price of carbon increases, the environmental cost of CO_2 emissions would increase as well. This in turn leads to an increase in the social cost of gas-fired power, making it more expensive compared to PV technology. However, it is estimated that PV power would only be competitive when considering the social cost of gas-fired power if the trading price of CO_2 is higher than 4400 NTD/ton. This shows that it is not possible to achieve the government's PV installation target by depending solely on a carbon trading system, though it is useful for the overall development of the renewable energy industry.

The discount rate is an important factor that affects financial cost. It reflects the installer's perception of opportunity cost and would directly affect the computation of PV power generation costs. This section discusses the sensitivity analysis that demonstrates how the discount rate impacts the highest deployment cost in various PV projects. The results are shown in Fig. 6.

Fig. 6 shows that lowering the discount rate is not enough to make PV power commercially viable. When the discount rate is reduced from 5.25% to 2%, the lowest deployment cost of the various PV projects that would achieve the 2020 target falls by approximately 2 NTD from 6.5192 NTD/kWh to 6.5280 NTD/kWh. The discount rate reduction is helpful in strengthening the price competitiveness of PV power generation, though the price is still higher than gas-fired power's social cost of 4.4 NTD/kWh.

Despite these challenges, the impact of the discount rate reduction on power generation costs should not be overlooked. A lower discount rate would speed up the process of PV commercialization. From the perspective of PV industrial development, implementation of more favorable policies by the government in addition to FITs can help lower the discount rate of PV equipment installation costs (such as electricity price and loan interest rates), and encourage the PV industry to invest in R&D.

5.2.1. Cost reduction

Reduced costs for specific installed capacities can be achieved through more efficient energy generation made possible through technological advancements in PV technology. Therefore, plans for the future direction of the PV industry are directly affected by the rate of technological improvements in PV power.

Table 8
PV potential and generation costs from the three types of PV equipment.

	Class I (1–10 kWp)		Class II (10–100 kWp)		Class III (100–500 kWp)	
Possible deployment	1879 MWp (1924 GWh)		939MWp (962 GWh)		939MWp (962 GWh)	
Lowest cost	6.7239 NTD/kWh		6.0404NTD/kWh		5.7210NTD/kWh	
Highest cost	15.3226 NTD/kWh		13.7650NTD/kWh		12.9854NTD/kWh	
Target year	2020	2030	2020	2030	2020	2030
Government target (power generation) [installed share]	512 MWp (647 GWh) [50%]	1550 MWp (1672 GWh) [50%]	256 MWp (323 GWh) [25%]	776 MWp (836 GWh) [25%]	255 MWp (320 GWh) [25%]	775 MWp (835 GWh) [25%]
Highest cost to achieve government target	9.1909 NTD/kWh	12.6610 NTD/kWh	8.2566 NTD/kWh	11.3739 NTD/kWh	7.7924 NTD/kWh	10.6783 NTD/kWh

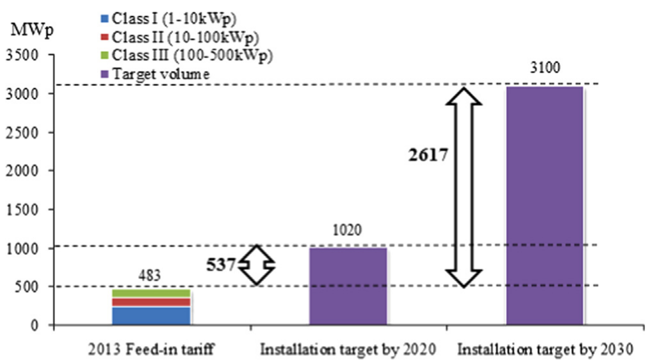

Fig. 11. The gap to reach the government target under 2013 feed-in tariffs.

If the cost of PV power generation decreases as low as the social cost of gas-fired power (4.19 NTD/kWh), then PV technology would be considered marketable. The curve in Fig. 7 shows that to reach a specific installed capacity, the cost of PV power generation has to be reduced by a certain percentage in order to be equivalent to the gas-fired power social costs. It also shows that when the cost of PV power generation goes down by 26.8%, then certain PV projects with costs lower than the gas-fired power social costs can be developed. In order to reach a usage target of 1020 MWp, the cost of PV power generation needs to go down by approximately 50.8%. A reduction in the cost of PV power generation by 64.8% in 2030 would be sufficient to develop PV systems that can achieve the target of 3100 MWp. Overall, in order to reach the government target, Taiwan needs to reduce PV power generation cost by at least 60%. This shows that the high deployment cost is the main reason for the sluggish growth of PV applications in the market.

A topic worth discussing is whether or not Taiwan can achieve the policy target by depending solely on technological improvements. Though PV power in Taiwan is still in its infancy, future costs are expected to go down substantially through technological advancements. Bloomberg's New Energy Finance estimated that large-scale PV installation costs would go down by as much as 50% by the year 2020, making it as low as 1.45 USD per watt in the US. Based on current trends, technological developments in PV power by Taiwanese suppliers should be at par with those coming from foreign firms. Therefore, the optimistic prediction made by Bloomberg about future cost reductions should be as applicable to Taiwan's PV technology as it is to its foreign counterparts. This can serve as a driving force for the government to fully support developments in PV technology to achieve its policy target by 2020.

In summary, the environmental costs of CO_2 emissions are a major factor influencing the cost of gas-fired power. As an indirect result of this, PV technology would become more commercially viable in the face of increased gas-fired power generation costs that would result from countries around the world placing higher standards on CO_2 emissions. Concurrently, the discount rate and technological improvements have a direct impact on the cost of PV power generation. The former impacts the public's view of long-term investments in PVs, while the latter would affect the rate of cost reductions for PV power generation. Thus, a lower discount rate or larger cost reductions for PV systems would increase the public's willingness to install PV systems and expand the domestic market for PV applications.

5.3. Analysis of government policy implementation

Section 5.2 discussed the primary considerations in PV promotion. In addition, we also need to consider that in the year 2013, Taiwan initiated different FIT rates for power generation equipment of different capacity classes. This section analyzes the challenges and obstacles to achieving the installation target based on the supply curves for different capacity classes.

In the following diagrams, we show the supply curves of three PV capacity classes. Figs. 8–10 show the deployment potential for each capacity class. The three supply curves indicate the maximum cumulated capacities of 1879 MWp, 939 MWp, and 939 MWp for each PV capacity class, while classes I, II, and III can produce 1924 GWh, 962 GWh, and 962 GWh of power, respectively.

The next thing to consider is the best allocation of the different PV capacities based on the proportions of the country's residential and industrial areas. For example, the target PV installed capacity for the year 2020 is1020 MWp. Table 8 shows that the best allocation of the different PV capacity classes is as follows: 50% or 625 MWp should come from PV category I and 25% or 312 MWp should come from each of the two other categories.

In addition, it is important to take a closer look at the deployment costs required by the various PV capacity classes in the process of achieving the government targets. The highest deployment costs required in each class to achieve the 2020 target are as follows: 11.6408 NTD/kWh for category I, 10.3563 NTD/kWh for category II, and 9.9549 NTD/kWh for category III. The costs required to reach the 2030 target are 13.9740 NTD/kWh, 12.4323 NTD/kWh, and 11.9089 NTD/kWh for PV capacity classes I, II, and III respectively. Cost is an important factor to consider because it determines the marketability of PV power. If the PV industry can bring deployment costs down to a level that is below or equal to the social costs of gas-fired power, PV energy would then be able to compete on price and generate enough revenue so that it would no longer need subsidies from the government. The required monetary investment, however, indicates that PV power is still too expensive to be price competitive, and therefore would still need some government funding.

Section 5.2 provides evidence that the ability to reduce deployment costs for PV power systems depends on improvements in PV technology. It is critical to improve PV technology if this energy source is to attain commercial viability in the future. This study also discovered that substantial reductions in costs are required for the government to achieve its PV installation targets. Taiwan aims to speed up the development of domestic PV applications by implementing the FIT mechanism. This study analyzes the FIT mechanism to determine if it can help achieve the government targets.

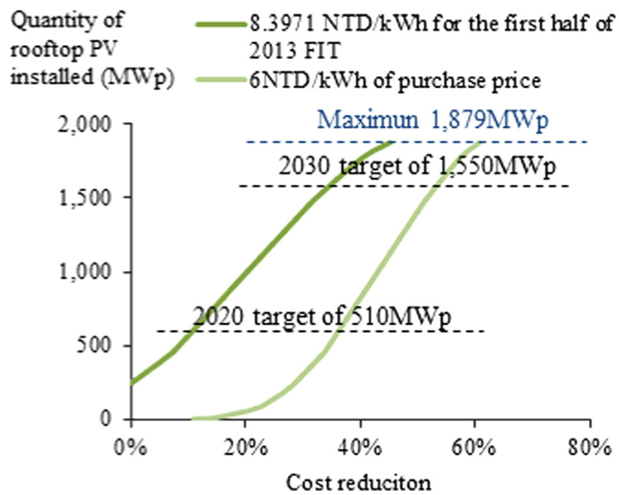

Fig. 12. Cost reduction required for class I (1–10 kWp) to achieve the target installation capacity under a given FIT.

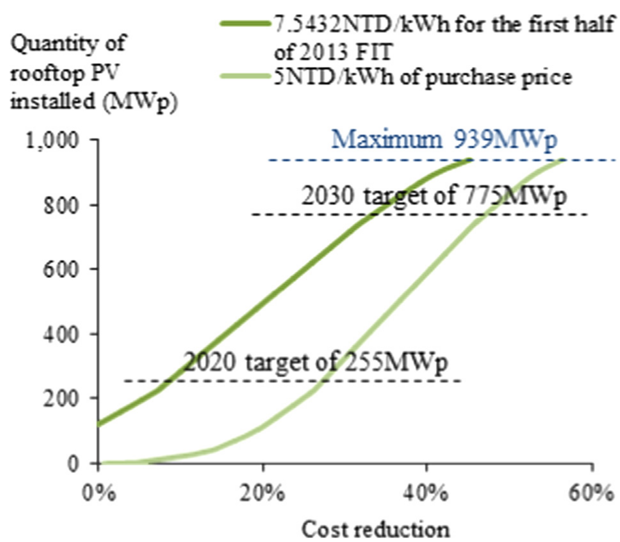

Fig. 13. Cost reduction required for class II (10–100 kWp) of PV generation to achieve the targeted quantity under FIT.

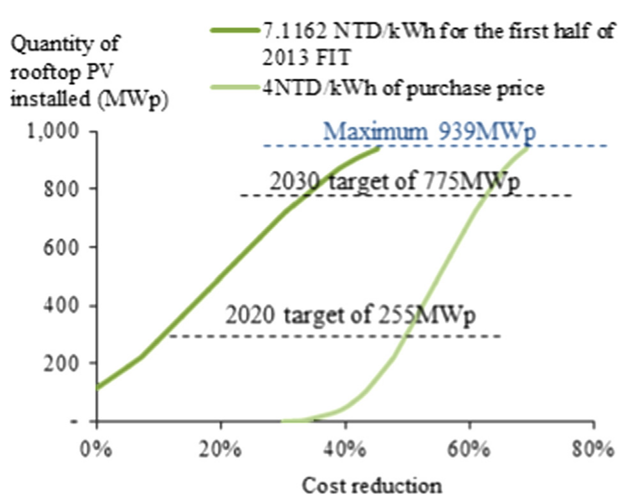

Fig. 14. Cost reduction required for class III (100–500 kWp) of PV generation to achieve the targeted quantity under FIT.

As stipulated in the 9th clause of the 'REDA,' the Ministry of Economic Affairs (MOEA) publishes the PV feed-in-tariff every year. This paper uses the FIT rates published in 2013 in its analyses and computations. As seen in Table 8, the rates for categories I, II and III are 10.3185 NTD/kWh, 9.1799 NTD/kWh, and 8.8241 NTD/kWh, respectively. FITs are designed to guarantee the purchase of PV power generated by independent power producers for 20 years using fixed rates, in a bid to boost investor's confidence for the long term and enhance international competitiveness [39].

The FIT system is expected to attract the public's participation in PV system installation, support the domestic PV applications market, and achieve policy targets. Fig. 11 compares the possible deployed volume given the 2013 FITs and government target. This result emphatically shows the gap between the potential quantity of PV applications and the policy target. The appropriate FIT rate should provide just enough incentive to boost PV deployment but not lead to overbuying renewable energy [16,30]. The target volume and power generation costs are correlated on any given FIT. This study shows the relationship between cumulated capacity and cost reduction rate, and explores ways that the target volume can be fulfilled. It is worth noting that in order to ensure the progress of Taiwan's renewable energy initiative, the FIT is revised yearly. For example, the 2011 revision reduced the FIT by 30% from its value in 2010. Technological advancements, which are expected to lower the generation cost over time, would compensate for the gradual reduction of FIT rates. Thus, this study assumes guaranteed purchase prices of 6, 5, and 4 NTD/kWh for the three PV capacity classes, which are below the 2013 FITs, in conducting its analyses. Figs. 12–14 show the cost reduction required to achieve the target installed capacities given different purchase prices.

Figs. 12–14 show that the FIT can indeed stimulate domestic PV demand. Consider the following scenarios. Without a FIT mechanism in place, achieving the target installation capacity of 1020 MWp would require a cost reduction of 50.8% (see Fig. 7). After implementing the FIT system, only an 8.7% reduction in cost would be required. In comparison, a lower purchase rate (compared to the 2013 FIT) would require a cost reduction of approximately 40% to reach the government target (see Table 9).

These simulation results reveal that (1) under any given FIT, a higher government target would require a more substantial cost reduction; (2) under any given government target, a higher FIT would require less reduction in cost; (3) under any given cost reduction rate, a higher government target would require a higher FIT. Thus, an overly high FIT might slow down the expected rate of reduction of installation costs for PV technology, which is detrimental to the technological progress of the industry. On the other hand, an overly low FIT would discourage participation from private entities and therefore would not help achieve policy targets. Hence, it is essential for the government to examine the optimal combination of PV installation targets, FIT rates and PV technological advancements. This paper intends to provide assessment tools that can help policymakers formulate decisions regarding PV energy.

6. Conclusions

This study aims to provide policymakers with assessment tools to simulate concrete scenarios and optimal conditions that would advance PV power as a viable renewable energy source in Taiwan. To do so, a PV supply curve was constructed to allow for techno-economic assessment in the various counties and cities of Taiwan. This assessment helps to explore the potential capacity of PV systems, the primary considerations of PV applications, and the feasibility of PV deployment policy.

This paper's numerical results show that the potential PV installed capacity on building rooftops is around 3758 MWp. Therefore, the government can reach the target of 1020 MWp by 2020 and 3100 MWp by 2030. This paper also investigates four primary considerations affecting domestic PV power generation: gas-fired

Table 9
Cost reduction required given different purchase prices to achieve policy targets.

Target year	Class I (1–10 kWp)		Class II (10–100 kWp)		Class III (100–500 kWp)	
	2020	2030	2020	2030	2020	2030
8.3971 NTD/kWh for the first half of 2013 FIT	8.64%	33.68%				
6 NTD/kWh of purchase price[a]	34.72%	52.61%				
7.5432 NTD/kWh for the first half of 2013 FIT			8.64%	33.68%		
5 NTD/kWh of purchase price[a]			39.44%	56.04%		
7.1162 NTD/kWh for the first half of 2013 FIT					8.68%	33.36%
4 NTD/kWh of purchase price[a]					48.67%	62.54%

[a] This study assumed guaranteed purchase prices of 6, 5, and 4 NTD/kWh for three PV capacity classes, which are below the 2013 FITs.

power generation costs, CO_2 emission costs, the discount rate, and potential cost reductions. Among them, cost reductions are the most important factor. From a financial perspective, it is difficult to achieve the government target solely through free market competition at this point in time. The high cost of PV power generation is the main obstacle to promoting PV applications. This study shows that technology improvements are crucial to achieve the cost reductions required before this project can be considered a sound investment.

A purchase rate that is too high can lead Taipower to overbuy renewable energy. It can also cause other problems including increased electricity prices and a weakened PV business (because additional income diminishes the willingness to invest in technological advancements) [31,40]. It is a great challenge to find a reasonable (not too high) purchase price for renewable energy [16,22,41].

Figs. 12–14 show the relationship between the FIT, target capacity, and cost reduction. These diagrams provide a strong foundation for policy analyses and FIT revisions in the future. The numerical results show that increasing the FIT can achieve the PV deployment target, but may lead to a heavy financial burden on Taipower. On the other hand, if the Taiwan government is confident that technological progress in the PV industry will be sufficient in the near future, then lower FITs would be acceptable. Therefore, an appropriate FIT needs to consider both the policy target and the expected rate of technological progress.

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